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Potential New Sources of Natural Gas

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Introduction

Natural gas continues to be one of the major sources of energy produced and used in the U.S. Declining gas reserves and curtailment of supplies have reemphasized the major influence this energy source has on the U.S. economy. The U.S. DOE is investigating several options for increasing the supply, including a program for unconventional gas recovery (UGR). Four UGR projects currently are being assessed: western tight gas sands, geopressured reservoirs, Devonian shales, and methane from coalbeds.

Both the Devonian shale and methane-from-coalbeds projects are paramount in this assessment, since they underlie a large section of the U.S.

The eastern (Devonian) shales contain a vast, essentially unexplored volume of natural gas. This area could represent new gas recovery from approximately 250,000 sq miles throughout the U.S. Studies by the government and industry have been focused on shale characterization to determine the magnitude of potential gas reserves and technology development needed to improve current state-of-the-art stimulation techniques. The initial R&D results have shown promise and point out the technology needed for successful development.

The goal of the methane-from-coalbeds project is to provide natural gas from coal seams. While coal itself is recognized as a major energy source, it also contains vast quantities of methane gas. This methane source is not new, since coal mine operators have been aware of its presence and release into the atmosphere during mining opertions. Technology studies are being conducted to learn the production potential of this methane and to show how this gas may be put to widespread use.

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Devonian Shales

The Devonian shales of the Appalachian, Michigan, and Illinois basins have produced natural gas since the 1800's. These shales in the eastern U.S. (Fig. 1) contain a high volume of gas. Independent estimates of the recoverable gas range from 3 Tcf to several hundred times that amount. To date, the gas produced from these shales has been limited to an estimated 2.5 Tcf[1,2] because of the unpredictable behavior and economics shown by existing Devonian shale wells. Similarly, these uncertainties have restricted private-sector R&D funding and development of technology needed for Devonian shale gas production.

Background

The DOE program for development of Devonian shale natural gas production is the Eastern Gas Shales Project (EGSP), which provides for a DOE-industry partnership to conduct projects that will

The U.S. DOE's gas resource program aims at resolving existing technological barriers to effective recovery of natural gas from Devonian shale and methane from coalbeds. Upon completion of these projects, DOE expects the technology developed jointly with industry to result in wide-scale recovery and use of these new sources of natural gas.

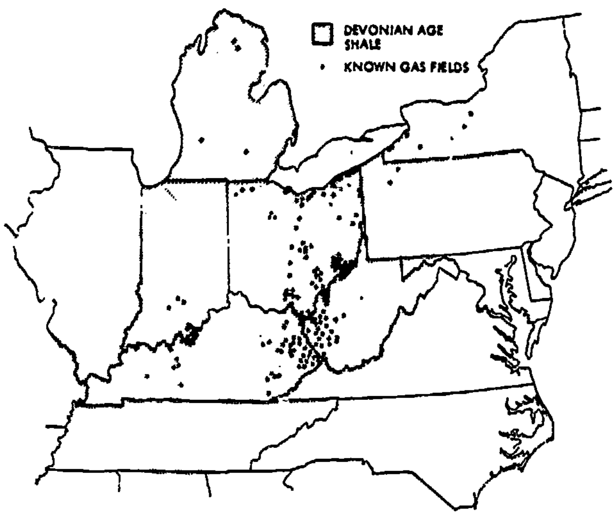

Fig. 1 – Distribution of Devonian shale gas fields with eastern shale gas basins.

produce the technology required to stimulate commercial development of Devonian shale gas. The project encourages private industry to initiate and direct R&D projects by sharing the risks and costs of development. Advancements in R&D technology will result in more effective and economical production of gas.

The DOE initiated the EGSP in early 1976 at the Mortgantown Energy Technology Center (METC). Full-scale implementation was begun in 1977 with about 30 contractors initiating the first phases of research activities. In addition, projects with industry were initiated to complement the shale characterization studies.

Table 1 highlights the accomplishments, current direction, and planned activities through fiscal 1983.

Purpose. The twofold purpose of the EGSP is to determine the magnitude of Devonian shale gas resources and to increase gas production from this shale. To develop the production on a commercial basis, three major problems associated with Devonian shales remain to be solved:

1. How large are the potential gas reserves associated with Devonian shales in each of the three basins?
2. How much of the reserves in each basin can be produced by employing both present and foreseeable future technologies (that is, what are the recoverable reserves of Devonian shale gas)?
3. What are the most effective technologies for extracting this gas, and which have the greatest cost benefit?

Reliable well production histories and stimulation test comparisons were limited and confined to relatively small geographic areas within the potentially productive areas of the three sedimentary basins. Laboratory data from Devonian shale cores have been too scattered in terms of geographic distribution and too sparse to yield reproducible results that could be used for each of the three sedimentary basins. A thorough evaluation of Devonian shale was required and initiated.

EGSP Project Participants. Contractors and agencies have been engaged to perform and/or support various EGSP activities. Table 2 lists project participants and their activities. Through the efforts of this project team, significant progress has been made in achieving EGSP goals and objectives. The contractors are responsible for advancing technological areas, while METC is responsible for overall coordination and management of the project.

In general, work on resource inventories is being conducted through contracts with state geological surveys and universities. The results are compiled and reported regionally by the USGS. Characterization studies are contracted to universities, research institutes, and private industry. R&D efforts to develop and improve current methods for gas exploration and production have been undertaken by contractual arrangements involving universities, research institutions, and private industry. Field testing of stimulation techniques is being conducted through cost-shared contracts with private industry, as are other DOE-sponsored enhanced oil- and gas-recovery field projects. This approach is designed to promote concurrent large-scale projects in different geographical areas and, by using a wide variety of techniques, accelerate the process of developing the more promising techniques to commercial status. Environmental impact assessments made for all field activities are treated as an integral part of each work activity. Economic analyses are performed to determine the cost benefits of various aspects of the project. Particular attention is given to the economic feasibility of current and projected technology that will apply to gas production.

Project Structure. Fig. 2 is a work breakdown for the EGSP, illustrating the various technical activities and how they relate to one another. These activities are the same as those shown in Table 2.

Resource Characterization and Inventory

The resource characterization and inventory element of the EGSP is divided into six areas necessary for gathering data: core and log acquisition, geological evaluation, physical characterization, geochemical characterization, exploration techniques development, and resource assessment.

Core and Log Acquisition. The objectives of core and log acquisition are to acquire a representative suite of Devonian shale cores and logs and to identify the set of logging techniques best suited for detection of gas-rich and fractured zones. The coring and logging activities used are intended to support both resource characterization and the design of extraction techniques.

Currently, more than 20,000 ft of Devonian shale cores have been collected for physical and geochemical tests (Fig. 3).

A typical suite of well logs run on an EGSP well included the following.

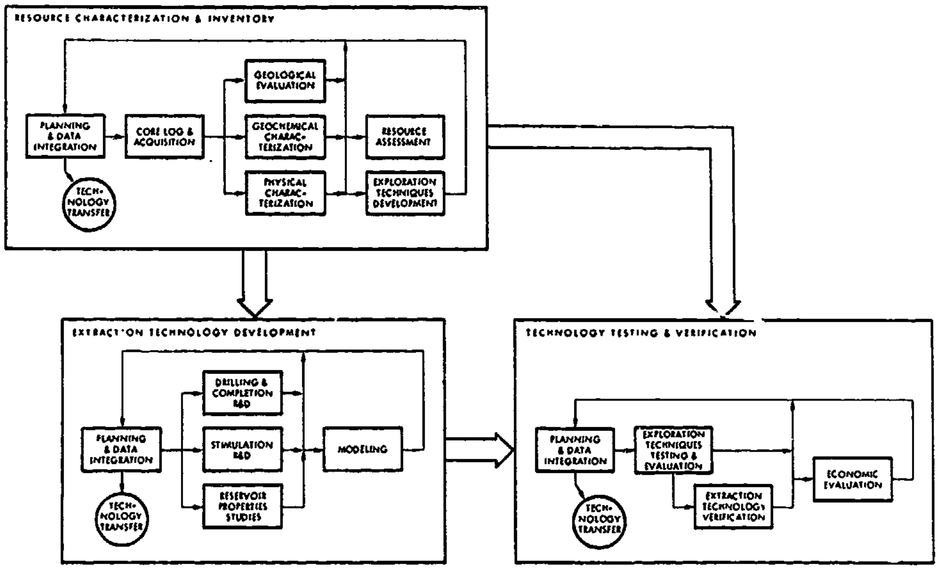

Fig. 2 – Flow diagram for EGSP activities.

Wet-Hole Logs

Compensated neutron
Gamma ray
Formation density compensated
Caliper
Dual induction
Laterolog^{TM}
Borehole compensated sonic
Variable density
Fracture identification
Coriband kerogen

Dry-Hole Logs

Gamma ray
Temperature
Sibilation/noise
Caliper
Formation density compensated

Efforts are under way to define the required logging suite that will yield maximum formation evaluation data at minimum cost. The full suite of well logs listed will be a prohibitive expense for the average operator. Present indications show that gamma-ray, neutron, bulk density, temperature, sibilation/noise, and induction logs may be sufficient, although the fracture identification log also may prove useful.

Geological Evaluation. The geological evaluation effort includes determining the distribution, thickness, lithologic variation, and geologic structure of the Devonian shale in the Appalachian, Illinois, and Michigan basins. The data is generated through stratigraphic, sedimentological, and structural analyses.

This data base is applied to exploration R&D by comparison of areas with known gas production to areas that have not produced gas. The relationships established from gas production, geological variables, and data from the well logging and core analyses can be used to predict areas with the greatest potential for gas production.

This data also provides important information needed in the resource assessment effort, as it yields information on the volume of shale and extent of known producing horizons as well as their thickness and structure. Further, it provides information on the direction, size, and concentration of natural fractures needed for production and stimulation R&D work and provides much of the data on reservoir characteristics needed for computer modeling.

Most of the effort has been in the generation of isopach and structure contour maps and cross sections of selected shale units by state surveys in the Appalachian basin. These maps and cross sections are being compiled and used for a Devonian shale gas assessment by the USGS. In addition to these basin-wide maps, various state surveys and several

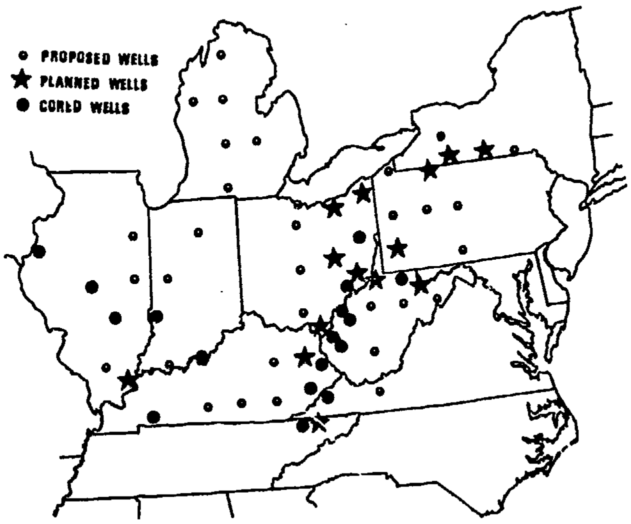

Fig. 3 – Map of EGSP core locations.

TABLE 1—EGSP ACCOMPLISHMENTS, CURRENT TASKS, AND PLANNED ACTIVITIES

	FY 76 AND FY 77 ACCOMPLISHMENTS	FY 78 MILESTONES	PLANNED ACTIVITIES THROUGH FY 85
RESOURCE CHARACTERIZATION AND INVENTORY	• Initial planning completed • Preliminary resource assessment and inventory • Preliminary reserve assessment • Development of characterization methods and techniques • Data collection initiated: geochemistry studies; outgassing experiments; diffusion, porosity, and permeability studies; physical and chemical characterization • Geologic evaluations initiated: Indiana, Illinois, Ohio, West Virginia, Kentucky, Pennsylvania, New York, Tennessee	• Stratigraphic framework: Pennsylvania, Eastern Kentucky, Western Kentucky, Ohio cross-sections • Structural framework: New York, Onondaga-Pennsylvania, West Virginia, Illinois contour maps • Geologic/production correlation: Pennsylvania, Western Kentucky, New York correlation maps • Density/gamma log assessment • On-going physical and chemical property measurements • On-going geologic evaluations	• Final resource and reserve assessments • Complete stratigraphic and structural frameworks for Appalachian, Illinois and Michigan Basins • Complete physical and chemical property measurements • Complete exploration techniques development for Appalachian, Illinois, and Michigan Basins
EXTRACTION TECHNOLOGY DEVELOPMENT	• Initial planning completed • Initiated Columbia Gas MHF test projects; drilled and stimulated 3 wells in Lincoln Co., WV • Initiated 13 well project (cryogenic/MHF, dendritic) by Columbia Gas System Service; stimulated and tested wells in Virginia and Ohio • Drilled well, conducted multi-stage foam stimulation treatment, completed gas production monitoring in Perry Co., KY, by Kentucky-West Virginia Gas Co. • Initiated 2 three-well chemical explosive tests in KY and WV by Petroleum Technology Corp. • Completed site selection for deviated well in Jackson Co., WV, by Consol Gas Supply Corp.	• Complete Columbia Gas MHF test project in Lincoln Co., WV • Drill and stimulate (cryogenic, MHF, and dendritic) 2 WV Benson wells and 2 Medina wells, by Columbia Gas System Service • Drill, core and stimulate MERC-1 well • Stimulate 3 wells with chemical explosives in Leslie Co. KY, by Petroleum Technology Corp. • Stimulate 2 wells with chemical explosives in Lincoln Co., WV, by Petroleum Technology Corp. • Initiate deviated well drilling by Consol Gas Supply Corp. in Jackson Co., WV • Complete configuration drilled well (RFP in process) • Complete fracture mechanics model • Decide on expansion, redirection of extraction technology R&D projects • Develop strategy for selection of stimulation techniques in specific geologic areas	• Complete 13 well project (cryogenic, MHF, dendritic) by Columbia Gas System Service • Complete evaluation of advanced hydraulic fracturing techniques • Complete evaluation of advanced explosive fracturing techniques • Complete evaluation of drilling and completion projects • Complete reservoir property studies • Complete production flow model • Complete induced fracture geometry model • Complete assessment of dual and/or recompletions in Appalachian Basin • Verify strategy for selection of stimulation techniques for specific regions
TECHNOLOGY TESTING AND VERIFICATION	• Initial planning completed • Pre-solicitation Bidders Conference I - Appalachian Basin	• Drill test wells for 8 Phase I sites • Preliminary Phase I reservoir evaluation • Well test planning for remaining 12 Phase I sites • Preliminary Phase II extraction technology planning	• Drill test wells for 12 additional Phase I sites • Phase I evaluation and detailed Phase II planning • Drill Phase II test wells • Evaluate Phase II test data • Economic evaluation

universities have compiled additional data on other Devonian units for specific contour and isopach maps. In the Illinois basin, the Illinois, Indiana, and Kentucky geological surveys are correlating and mapping the main black shale members of the New Albany shale. The Indiana Geological Survey also is mapping a small portion of the Michigan basin. Additional isopach and structure contour mapping and cross sections will be done, with emphasis on more detailed mapping of areas selected as potentially gas productive.

Results of structural studies in Cottageville gas field in western West Virginia by West Virginia U.[3] indicate that the development of fracture facies may be related to fault movement in the basement (Rome trough) structure. The USGS and the Kentucky Geological Survey are investigating surface and subsurface structural features associated with and surrounding the Rome trough in the Appalachian basin. According to West Virginia U.[4] investigations of slickenslides and natural fracture trends from a Wise County, VA, core indicate that there is rough agreement with the direction of movement for the Pine Mountain thrust sheet. With further verification of this relationship, the occurrence of porous fractions associated with these features (slickenslides and natural fractures) may be predicted. Natural porous fracture systems are primary targets in obtaining gas production from the Devonian shales.

Mapping of lineaments in the Appalachian and Illinois basins is being done at regional and site-specific scales. Numerous site-specific lineament maps have been prepared for prospective exploration target areas. Three main problems in using lineaments for exploration have been identified[5]: unknown relationship of lineaments to geologic structure and gas production, operator mapping skill and bias, and scale (for example, LANDSAT vs. aerial photos).

Data for a computer model of Devonian shale in the Appalachian basin is being compiled. According to the U. of Cincinnati,[6] preliminary analysis of

TABLE 2 – EGSP PROJECT PARTICIPANTS AND ACTIVITY AREA

	WORK PACKAGE													
CONTRACTOR	CORE & LOG ACQUISITION	GEOLOGIC EVALUATION	PHYSICAL CHARACTERIZATION	GEOCHEMICAL CHARACTERIZATION	RESOURCE ASSESSMENT	EXPLORATION TECHNIQUES DEVELOPMENT	DRILLING & COMPLETION R&D	STIMULATION R&D	RESERVOIR PROPERTY STUDIES	MODELING	EXPLORATION TECHNIQUE TESTING & EVALUATION	EXTRACTION TECHNOLOGY VERIFICATION	ECONOMIC EVALUATION	PLANNING & DATA INTEGRATION
AMEX/VESCORP						●								
BATTELLE, COLUMBUS LABS			●	●					●	●				
COLUMBIA GAS	●		●	●		●		●	●					
CONSOLIDATED GAS SUPPLY	●		●	●		●	●							
ENVIR. & REGIONAL RES. ASSOC.														
ENVIR. RESEARCH INST. OF MICH.						●								
GRUY FEDERAL INC.		●							●					
ILLINOIS GEOLOGICAL SURVEY		●	●	●										
INDIANA GEOLOGICAL SURVEY		●	●	●										
JAYCOR											RFP's IN PROCESS	CONTRACTORS TO BE IDENTIFIED		●
JUNIATA COLLEGE			●	●										
KENTUCKY-W. VA. GAS CO.	●					●	●	●						
LAWRENCE LIVERMORE LABS	●					●				●				
LOS ALAMOS SCIENTIFIC LAB						●		●		●				
MERC	●	●	●	●	●	●	●	●	●	●			●	●
MID-STATE UTILITY & GAS								●						
MOUND LABS		●	●	●					●					
NEW YORK GEOLOGICAL SURVEY		●		●										
NORTHERN ILLINOIS GAS	●		●	●										
OHIO GEOLOGICAL SURVEY		●	●	●										
PENNA. GEOLOGICAL SURVEY		●												
PEOPLES NATURAL GAS CO.								●						
PETROLEUM TECHNOLOGY CORP.	●						●	●						
REEL ENERGY COMPANY	●							●						
RIVER GAS COMPANY	●													
SANDIA LABS						●	●	●		●				
SCIENCE APPLICATIONS INC.					●					●				●
STANFORD RESEARCH INST.			●					●		●				
TENNESSEE GEOLOGICAL SURVEY	●	●				●								
TRI-STAR PRODUCING CO.	●													
TRW ENERGY SYSTEMS					●								●	●
U. S. GEOLOGICAL SURVEY		●	●	●	●	●								●
UNIVERSITY OF CINCINNATI		●	●	●		●								●
UNIV. OF KY. RES. FOUNDATION		●	●	●										
UNIVERSITY OF NORTH CAROLINA		●												
UNIVERSITY OF SO. CALIFORNIA				●										
WELCH & ASSOCIATES	●							●						
W. VA. GEOLOGICAL SURVEY		●	●	●	●									
W. VA. UNIVERSITY		●				●		●						

paleocurrent indicators in parts of the Appalachian basin shows that the eastern two-thirds of the Upper Devonian shale sequence has uniformly westward-oriented paleocurrents. This is an initial step in developing a geological model of the Appalachian basin to include directions of sediment transport, environments of desposition, types of sediments being deposited, structural deformation, and location of the source of these sediments. A model of the Catskill delta in the basin has been completed by the West Virginia Geological Survey.[7]

Physical Characterization. This activity is designed to record and describe lithology, fracture characteristics, and index, directional, and flow properties from the core. The data obtained will aid in the estimation of the reserves and in the determination of the methods needed for exploitation of the gas.

Preliminary laboratory data from the Illinois State Geological Survey[8] point to a relationship between fracture orientation and lithology. Bulk density work by Battelle Columbus Laboratories[9] shows an inverse correlation with gas volume. Schmoker[10] of the USGS, has shown that negative correlation of bulk density with gamma-ray intensity exists.

The porosity data compiled by Battelle Columbus show a range of values for samples from less than 0.1% to greater than 24% total porosity. The mean total porosity for seven wells ranged from 1.6 to 15.8%, with the open porosity accounting for one-third of the pore space. The average value for open porosity ranged from 0.6 to 12.2%. Effective porosity of the shale formation still remains an uncertainty. Statistical analysis shows no relationship between porosity and core outgassing volume. Two of the Illinois basin wells showed unusually high porosity with little or no core gas volume.

Permeability of samples ranged from 0.0 to 0.1 md. Permeability was tested both perpendicular and parallel to the bedding plane, and no significant differences due to direction were indicated. Currently, the shale has shown a somewhat uniform low permeability, even in samples that have yielded relatively large volumes of gas.

Geochemical Characterization. The gas content of the shale, as determined geochemically from measurement of encapsulated samples, will be combined with geological data to predict areas and stratigraphic horizons that have the greatest potential for producing gas.

Characterization studies have been completed on 16 wells. The tests show mineralogy to be relatively constant. The samples were composed of quartz and clay materials, and fractures generally were filled with calcite or pyrite.

The shale samples studied by the Illinois survey[8] were extensively laminated and composed of either silt grains and coarse organics in a matrix of clay and fine organics or of less silt and coarse organics. Laminae thickness ranged from <2 to >25 mm. The laminations may influence fracture orientation but apparently have no effect on permeability.

Elemental analysis of the shale by Leventhal and Goldhaber[11] of the USGS has shown that uranium correlates with carbon and that a negative correlation exists between the thorium/uranium ratio and carbon. Work by Battelle Columbus[9] has demonstrated positive correlation between carbon and gas volume and an inverse correlation to density. Because bulk density also is correlated inversely to gas content, gas-rich zones in the cores should be indicated by a combination of gamma-ray and density logs.

METC in-house assessment studies have determined that the average gas content for the wells tested ranged from 0.003 to 1.53 and averaged 0.52 cu ft gas/cu ft shale in the Appalachian basin and 0.42 cu ft gas/cu ft shale in the Illinois basin.* Illinois basin wells tended to have lower percentages of gas composed of the lighter hydrocarbons (C_1 through C_7) than the Appalachian basin wells.

Exploration Techniques Development. Wells drilled to or through the Devonian shale sequence often encounter shows of gas. EGSP studies have determined that there are large volumes of gas in place over wide areas of the three basins. This gas is thought to be absorbed in the shale matrix, adsorbed on natural fracture surfaces, and existing as free gas in the fractures. To extract the gas, natural fracture systems must be intercepted by the wellbore and artificial fractures created by stimulation to link the natural systems.

Exploration work has centered on the application of geological, geophysical, and remote-sensing techniques to Devonian shales to determine lineaments and other geologic features that might indicate fracture systems and high gas potential.

As a result of the various exploration techniques being investigated (standard mapping,[12] lineament mapping,[12] and seismic investigations[13]), wellsites have been chosen in West Virginia, Ohio, Virginia, and Kentucky.

Resource Assessment. Devonian shale characterization efforts presently being conducted should provide some understanding of reservoir characteristics. As proposed by deWys and Shumaker,[3] gas production from Devonian shale reservoirs could have three distinct origins. Initial production would be dominated by the free gas contained in the larger interconnected fracture system encountered by the well or in artificially induced fractures. Later, the adsorbed gas on the fracture surface would be released; finally, chemically absorbed gas could be released.

Laboratory experiments are being carried out to measure the amount of gas released from core samples from shale wells in various areas of the Appalachian, Michigan, and Illinois basins. Data accumulated so far continue to indicate that a large amount of gas is present in the Devonian shale sequence. Present estimates show approximately 700 Tcf is available in the Appalachian basin and ap-

*Data compiled from numerous quarterly and monthly progress reports from Mound Facility and Battelle Columbus Laboratories.

proximately 150 Tcf in the Michigan and Illinois basins.

Extraction Technology Development

The development of extraction technology to increase gas production from Devonian shale is divided into four primary areas: drilling and completion R&D, stimulation R&D, reservoir properties studies, and modeling.

Drilling and Completion R&D. Field operations activities are summarized as follows.

State	Devonian Shale Test Wells	Devonian Shale Core Wells
WV	10	6
KY	5	3
OH	2	2
VA	1	1
IN	1	1
IL	3	3
Total	22	16

Reservoir Properties Studies. The shales contain no significant free (mobile) water. When exposed to fluids in the borehole, they react both chemically and physically with the fluids. These reactions create compositional and structural changes resulting in formation damage, which can cause gas flow to decrease, or even stop if the damage is severe.

Shale swelling tests, adsorption isotherms, and clay composition of shale core samples have been determined. Results by Chenevert[14] indicate that clay swelling caused by water adsorption may not be as serious a problem in Devonian shale as it is in other gas-producing regions. Devonian shale is composed primarily of nonswelling illitic clay; montmorillonite has not been detected.

Stimulation R&D. Preliminary results of stimulation tests in Devonian shale are inconclusive. However, these analyses emphasize trends and should not be interpreted as conclusions because replicated data in various geological conditions do not exist. Of 20 wells stimulated, only seven have had open flows ≥ 300 Mcf/D (Table 3). A rationale for stimulation treatments presented by Komar[15] was based on black shale thickness and natural fracture density. His statistical analysis of Devonian shale well data indicated that hydraulic fracturing was an improvement over borehole explosive stimulation in areas of low fracture density. The data showed that in areas of high fracture density, displaced liquid chemical explosives and/or cryogenic fracturing were an improvement over conventional borehole explosives.

Yost[16] showed a comparison of hydraulic-fractured well production vs. wellbore explosive well production for an area peripheral to an eastern Kentucky gas field. Results indicated that hydraulically fractured wells (using gelled water and sand) produced 53 MMcf more gas after 5 years' production and produced at a rate 71% faster than wells stimulated by wellbore explosive methods. Since the inception of the program, 36 stimulation treatments have been performed in 22 Devonian shale wells. From these treatments, the following results and problems have been identified.

1. Columbia Gas Transmission Corp.[17] determined that massive hydraulic fracture (MHF) treatment using gelled water and sand is not a viable technique to use in a low-pressure tight shale reservoir due to problems associated with cleaning up the fracture fluid from the formation.
2. Columbia Gas and METC,[18] in association with Intercomp Resource Development & Engineering Inc., have determined that conventional modeling and well-test analysis cannot be used to evaluate the results of stimulation treatments in Devonian shale.
3. Low-residual hydraulic fracture fluids are useful in shale when using MHF treatments for reservoir fluid cleanup.
4. Results have been very good for wellbore chemical-explosive fracturing; however, costs are high, wellbore cleanout is required, and conclusions on effectiveness are incomplete.
5. Hydraulic fracturing techniques using foam or other fluids appear to be approaching commercial viability.

Modeling. Modeling activities have been split into fracture stimulation and production modeling. In fracture stimulation modeling, the efforts have been directed toward theoretical and experimental research on hydraulic fracturing by Lawrence Livermore Laboratory.[19] Some conclusions drawn from their work have been (1) an understanding of the significant effects of in-situ stress fields on fracture geometry and (2) that changes in pore pressures due to invasion of fracturing fluid can reduce the tendency to retard fracture growth. Other efforts include Stanford Research Inst.'s examination of the feasibility of enhancing fracture formation and growth in well stimulation by tailored pulse-loading. In this effort, various rock properties of relative and absolute importance to fracture by pulse-loading will be determined. A team approach to this evaluation involving contributions from Stanford Research Inst., Sandia Laboratories, Science Applications Inc., and the U. of Maryland is now in progress.

Fracture growth and orientation are being studied by Sandia Laboratories,[20] and the surface electrical potential system has shown that fracture orientation can be determined to within ±5° and that most fractures are asymmetrical.

Future efforts will include development of models to simulate production flow through shale and to show the effects of gas desorption on production.

Technology Testing and Verification Studies (TTVS)

For the purposes of the EGSP and TTVS, the Appalachian, Illinois, and Michigan basins have been divided into 11 areas based on evaluation of known and postulated geologic structures, type and extent of the natural fracture systems, and the historical gas production data. Testing will be conducted in two phases in each area through Oct. 1985. Phase 1 will involve drilling up to 20 sets of three screening wells within the 11 areas. Based on the results from the screening sites and on the data generated in the resource characterization and extraction technology development studies, 11 Phase 2 sites will be selected for more detailed field development. At each site, 8 to 10 wells will be drilled. Private industry will participate in both phases through cost-sharing.

During Phase 1, the data developed will be used to locate the areas and wellsites most likely to yield the greatest gas production. Additional data acquired from drilling these wells will be added to the data base.

Phase 2 activities will include evaluation of selected stimulation techniques – e.g., MHF (foam/water), MHF (foam), and cryogenic, dendritic, and explosive fracturing. This will provide stimulation R&D data.

An economic analysis will be conducted to evaluate the various stimulation techniques to determine the most cost-effective methods for completing a well in the Devonian shale.

TTVS Areas. For fiscal 1979, eight areas have been identified for cooperative government/industry drilling, stimulating, and completion. The exploration criteria used in determining the areas were (1) relation to known surface structures, (2) relation to known or postulated basement structures, (3) LANDSAT-derived lineaments, (4) other mapped lineaments, (5) thickness of black shale, (6) thermal maturity of black shale, and (7) gas content from black shale cores.

The first four criteria would be used in the

TABLE 3 – PRELIMINARY RESULTS OF STIMULATION TESTS IN DEVONIAN SHALE THROUGH AUG. 1978

Well No.	Zone	Type Treatment	Treatment Size 1000 Gallons	Initial Open Flow After Frac, Mcf/D	Total Gas/Well Mcf/D
Columbia 20401	1	MHF	517	110	
	2	MMHF	104	111	
	3	MMHF	100	80	
	4	MMHF	115	21	322
Columbia 11236	1	CO_2	117	36	
	2	CO_2	113	NA	36
Columbia 20403	1	MHFF	250	110	
	2	MHFF	320	200	
	3	MHFF	346	107	
	4	MHFF	347	NT	381*
Consolidated 12041	1	MHFF	163	173	173
KY-WV 7239	1	Foam	46	0	
	2	Foam	48	42	
	3	Foam	44	0	
	4	Foam	45	0	≈60
KY-WV 7246	1	Foam	50	337	337
Ray Clark #1	1	Foam	50	2	2
KY-WV 1627	1	Foam	50	103	103
PTC 686-1	1	CEF	3	260	260
Columbia 20338-T	1	CO_2	98	54-107	
	2	CO_2	112	40	150
Welch 1-15	1	Foam	46	550	550
PTC 686-2	1	CEF	3	300	300
Columbia 20337	1	CO_2	43	133	
	2	CO_2	39	NT	133
Columbia 20336	1	CO_2	61	370	
	2	CO_2	64	250	620
Peoples	1	MHFF	NA	Mechanical Failure	
PTC 686-3	1	CEF	3	310	310
Reel Energy	1	CO_2	Initially good open flows,		
	2	Foam	but made too much water.		
MERC-1	1	CO_2	105	0	
	2	CO_2	50	12	12
Columbia 20402	1	MHFF	≈150	145	
	2	MHFF	≈150	139	145
PTC 685-2	1	CEF	3	350	350

* Measured before frac Zone 4 (but communications existed between all zones)

MHF - Massive Hydraulic Fracture
MMHF - Modified Massive Hydraulic Fracture
MHFF - Massive Hydraulic Foam Fracture
CEF - Chemical Explosive Fracture.

(NA -- Not Available: NT -- Not Taken)

development of extensive natural fracture systems. The thickness of the shale sequence coupled with the thermal maturity and core gas-content data will yield information on potential gas recovery from the area.

Present Status

A vast amount of data has been collected in the resource characterization and inventory element of the EGSP. For the geologic evaluation, basin-wide sets of interlocking straigraphic cross sections, maps of previous gas production from the shale, and isopach and structure contour maps of the radioactive zones of the black shale have been prepared. Physical data have been compiled for 16 wells in the Appalachain and Illinois basins, including lithologic descriptions and index, directional, and flow properties. Geochemical data compiled on the same 16 wells included mineralogy, elemental analysis, gas content, organic analysis, and maturation analysis.

This pool of data has provided the information needed for resource assessment and the data base. Relationships between gas content and geologic, physical, and geochemical variables within the shale are beginning to emerge, and a set of characteristics associated with high gas content has been established.

Data have been compiled on the results of shale stimulation testing, but the wells have not produced long enough for evaluation. The process of gas flow through shale is being investigated through modeling techniques.

Technology testing and verification of areas of potential production have been delineated and ranked according to geologic setting. Preliminary data show the types of stimulation treatments likely to work in a given area.

Coalbed Methane Recovery and Use

Another source of gas is the methane that occurs naturally in most coal formations. The gas is believed to have been produced during the transformation of vegetation to coal during geologic time and retained within the coal seams by virtue of their low permeability and diffusivity. Coal mining operators have been acutely aware of its existence due to the safety hazards caused by release during mining operations. Accordingly, the coal mining industry has regarded the methane as a by-product that must be removed to provide safe mining conditions. In most instances, methane removal is accomplished by ventilation systems that vent methane/air mixtures to the outside atmosphere.

The first use of methane from coalbeds was through the R&D efforts of the U.S. Bureau of Mines (USBM). Although the USBM work, conducted jointly with industry, was intended to alleviate the methane hazard to mining, the methods used lent themselves to methane recovery as an added incentive. As a result of this work, a data base was established from which estimates of the size of the methane resource have been made. Those data indicated a gas-in-place magnitude between 300 and

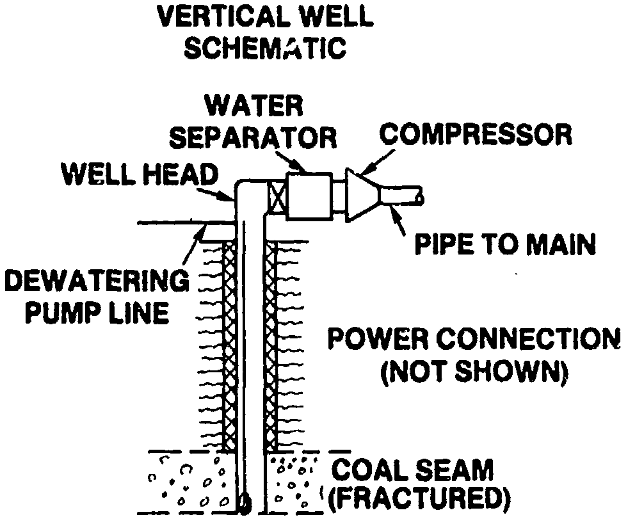

Fig. 4 – Methane coalbed drainage using simulated vertical wells.

800 Tcf from a combination of minable and unminable coal seams.[21,22]

Background

The USBM research program on methane-control technology began in 1964. That program addressed effective methane recovery from minable coal to provide improved and more cost-effective mine safety conditions. Several degasification methods were investigated: (1) vertical boreholes from the surface into virgin coal, (2) vertical boreholes into gob areas, (3) horizontal boreholes from ventilation shafts, (4) horizontal boreholes from underground mine workings, and (5) directional slant holes into virgin coal.

The vertical borehole method consists of drilling gas wells into coal formations before mining operations (Figs. 4 and 5). Borehole depths range from 250 and 750 ft. Because coalbeds typically contain water, the wells must be dewatered periodically to maintain gas production. Gas production by natural flow ranges from 500 to 10,000 scf/D in the Pittsburgh coalbed. Increased gas production of between 15 and 40 Mcf/D can be obtained by hydraulic stimulation. Foam stimulation using nitrogen as the foaming agent further increases gas production to between 40 and 100 Mcf/D. Vertical boreholes used to drain methane from gob areas can remove up to 1 MMcf/D methane from a mine and reduce underground gob emission by more than 50%.

Horizontal boreholes can be drilled radially outward from ventilation shafts[23] before mining to provide methane drainage as shown in Fig. 6. Results of USBM demonstrations indicate that methane emissions both at the mining face and along the rib are reduced significantly by this method. Seven horizontal boreholes have been used to drain methane at the multipurpose borehole[24] and at the Honey Run shaft of Federal No. 2 mine in the Pittsburgh coalbed. Since Sept. 1972, 1 Bcf of gas has been drained from the multipurpose borehole, with

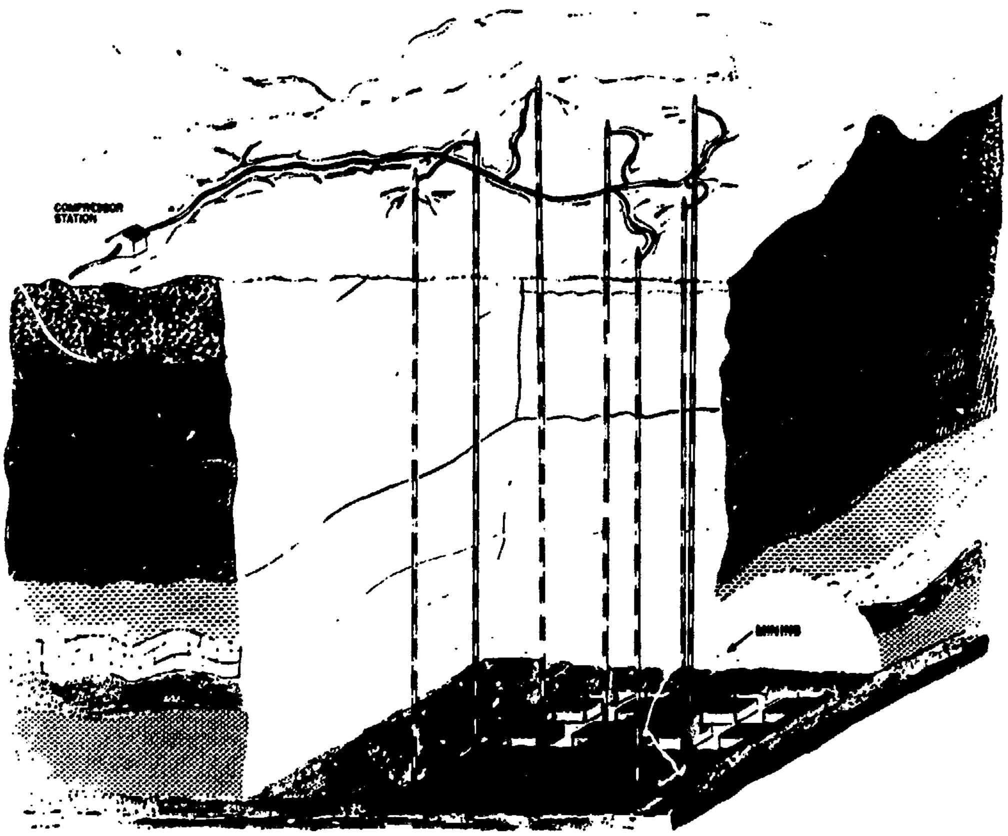

Fig. 5 – Vertical well method for methane drainage before coal mining operations.

an average production rate from seven horizontal boreholes of 570 Mcf/D. Gas drained from the Honey Run shaft totaled 880 MMcf in 3.7 years, with an average production from five boreholes of 650 Mcf/D.

Horizontal holes were drilled to drain gas in underground workings. Holes were drilled in outside entries at a slight angle, ahead of an active face. The drained gas was conducted to the surface via a gas-gathering pipeline system. This technique is used in the Pittsburgh and Sunnyside[25] coalbeds; similar drainage projects are planned for coal mines in Alabama, West Virginia, Pennsylvania, and Oklahoma. In 8 months, 46 MMcf of gas was drained from two relatively short holes in the Sunnyside coalbed.

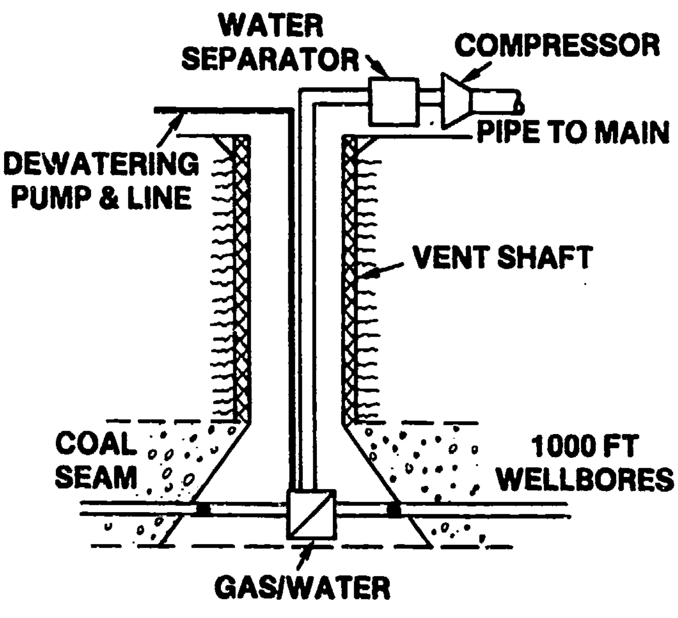

Fig. 6 – Vent shaft with horizontal boreholes for methane coalbed drainage.

The directional slant hole method shown in Fig. 7 currently is being investigated by the USBM. This method combines the efficient drainage characteristics of horizontal boreholes with the lower cost of small-diameter boreholes drilled from the surface. The slant hole is drilled from the surface at an angle to intercept the coalbed horizontally. In one test[26] a slant hole was drilled to the Upper Freeport coalbed, 930 ft deep, and continued horizontally for 390 ft. Results from the test showed that problems in bit control, downhole surveying, dewatering, and exploratory drilling must be resolved before slant drilling methods can be applied routinely.

Of all the methane produced from methane-control tests conducted by the USBM, less than one-third of the gas removed has been used either commercially or locally by the coal producers. However, these projects have demonstrated (1) the feasibility of methane removal as a contribution to safe coal mining conditions and improved mine productivity and (2) the feasibility of sustained production of methane gas that could be made available for commercial applications.

The Methane Recovery From Coalbeds Project

(MCBP) began in Oct. 1977 as part of the DOE program for enhanced gas recovery from unconventional resources. The overall goal of the project is to develop methods and systems for technical and economical recovery and use of methane from coalbeds. Specific objectives of the project include (1) location and evaluation of methane resources and establishment of proved reserves, (2) development of improved, cost-effective methane recovery and utilization technology along with mine development methods, (3) development of methane gas conservation techniques and systems, (4) development of methane recover production/projection techniques, (5) development and field testing of pilot systems, (6) investigation of legal and institutional constraints, and (7) transfer of the technology to industry.

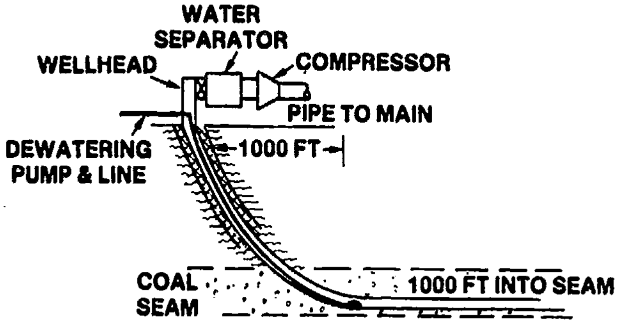

Fig. 7 – Methane coalbed extraction by directional slant method.

Project Overview. MRCP includes four main elements: (1) resource delineation – identification and definition of the coalbed methane resource; (2) R&D – development of improved, more cost-effective methods for conservation, recovery, and use of methane; (3) pilot system application – demonstration of the technical and economic viability of a number of different system/coalbed combinations to accommodate the variety of specific site conditions; and (4) project integration – coordination of project functions (technical overview, drilling planning, pilot systems planning, support studies/analyses, information management, and technology transfer).

The interrelationships of these four elements are shown in Fig. 8 and discussed in more detail as follows.

Resource delineation is required to assess the overall benefits of the commercialization of methane from coalbeds. Resource evaluation of coalbed methane has been accomplished only to a very limited extent, mostly in conjunction with active mining operations. Historically, because about 80 to 90% of U.S. coal has been produced from the Pittsburgh area most characterization work has been limited to that area and to only minable coal. Furthermore, previous work was concerned not with recovery and use of methane but rather with its removal to provide safe mining conditions. Consequently, relevant information has not been cataloged.

The resource delineation element of the project is collecting and assimilating relevant data from existing sources. The effort includes: (1) development of an overall methane resource delineation plan, (2) development of core sample drilling plans, (3) acquisition of characterization information – existing data sources and core samples from additional coalbed locations, (4) analysis and evaluation of all available data, (5) identification of potential recovery system sites, (6) development and confirmation of reservoir stimulation models, and (7) transfer of

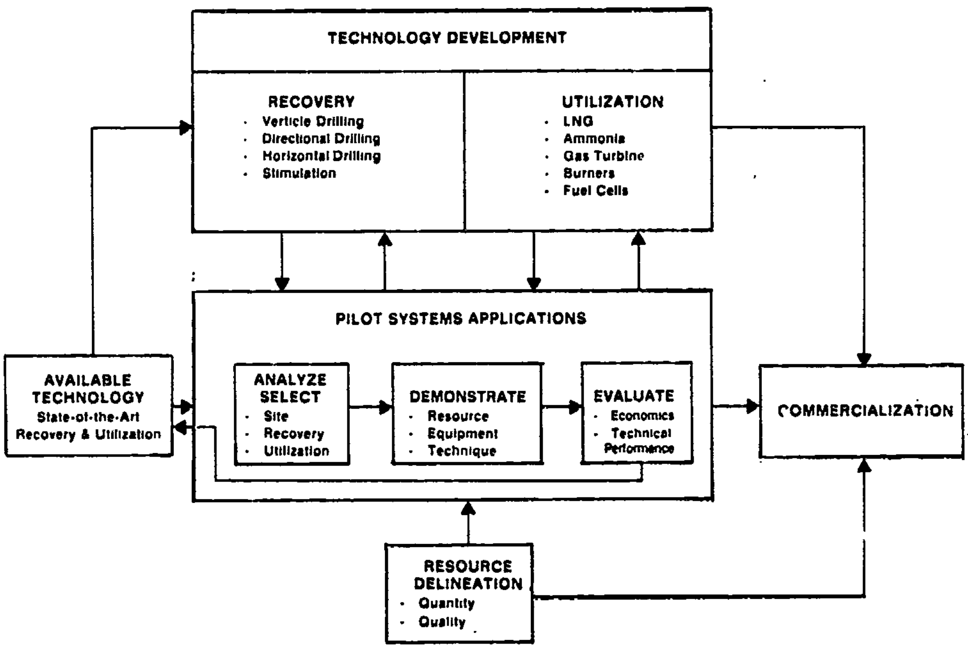

Fig. 8 – MCBP project interrelationships.

information to a repository available to potential users.

Data acquisition for resource delineation involves many sources outside the DOE such as the USBM for field and laboratory data from their projects; the USGS for integrated geologic data on coal seams throughout the U.S.; the state geological surveys for relevant geologic data from state projects; and universities, national laboratories, and oil and gas operators and coal companies with various types of research and analysis data relevant to methane resources.

The R&D element of the MRCP covers the recovery and utilization aspects of commercialization. Currently, the natural gas pricing structures offer insufficient economic incentives for widespread commercial interest in such resources. Because of this, R&D investigations that provide the data base and improve recovery utilization systems are essential. Specific recovery methods of the USBM work[27] are discussed in the preceding background section. Utilization subsystems include (1) direct injection into commercial pipelines, (2) conversion to ammonia, (3) conversion to LNG, (4) heating applications, and (5) power generation through gas turbines.

These recovery methods are available and have been used for methane recovery from coal seams; however none of them has been developed optimally relative to cost effectiveness. For example, multiple vertical wells are required for effective drainage of methane before mining, for which the spacing and location pattern of wells is critical to both safety and coal productivity. To resolve these and other issues relevant to eventual commercialization by industry, these R&D projects for methane recovery are planned: (1) development of improved equipment and techniques for directional drilling, (2) development of advanced fracturing techniques to provide more effective stimulation with resultant increase in gas flow, (3) development of improved dewatering techniques to provide more effective gas flow, (4) development of improved drainage techniques for more economical recovery and to assist productivity when active mining is involved, and (5) development of prediction techniques such as reservoir modeling applications.

The five utilization subsystems listed above are now technically feasible.[28] However, their economics in a commercial environment has not been demonstrated. Selections for pilot system applications will consider operational, institutional, and economic factors such as volume and quality of the gas, environmental aspects, and cost effectiveness of the utilization method. To provide improved and efficient utilization subsystems for specific applications, design modifications of existing equipment and new technology development are required. R&D projects currently are planned for these utilization processes: (1) LNG conversion, (2) ammonia conversion, (3) mixed gas utilization, (4) gob gas burning for heating applications, and (5) gob gas feedstock to gas turbines.

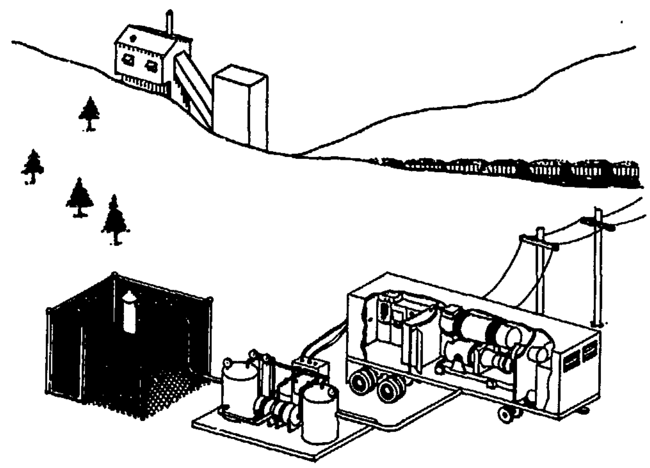

Fig. 9 – Pilot system for power generation from gob gas extraction.

The R&D efforts described will result in the development of commercially viable recovery and utilization of methane from minable coalbeds that would otherwise be wasted. This is a form of energy conservation, since methane from minable coal seams will provide additional energy reserves for future consumption.

Pilot system applications, jointly funded by the DOE and industry participants, are planned to investigate the impact of production variables that will be encountered under field conditions. An example of power generation from gob gas extraction is illustrated in Fig. 9. Collectively, these applications encompass methane recovery from both minable and unminable coal sources, as well as a variety of different recovery and utilization techniques. The planned projects are presented in Table 4. Ultimate commercialization of methane from coalbeds depends on the integration of specific recovery and use; an important objective of the pilot system is to demonstrate that capability. As shown in Table 4, pilot systems have been selected to accommodate the characteristics of differing coalbeds relative to methane recovery and use.

It may not always be possible to extrapolate results of pilot-system recovery methods to coalbeds of varying physical and chemical characteristics. In such instances, additional pilot projects may be required to demonstrate fully the recovery potential of coalbed sources. Pilot system testing will be a significant cost element of the MRCP. Reservoir studies accompanying these tests will help identify targets for pilot applications.

Summary

The occurrence of natural gas in Devonian shale is belived to differ from conventional gas occurrences in that the majority of gas apparently accumulates in natural fractures that serve as reservoirs and conduits for movement of the gas to the wellbore. Because the low gas production rates for conventionally developed Devonian shale gas wells have not been economically attractive, efforts have been directed toward understanding and identifying the natural fracture systems and toward developing techniques to make these fractures communicate with the wellbore.

The initial 3-year effort for the EGSP has had the support of more than 40 contractors engaged in various segments of the project. These efforts will provide the basis for continuous expansion of Devonian shale resources and answer many of the unresolved technology issues.

Little work has been done on methane recovery from coal formations considered unminable due to the poor economics of mining operations at excessive depths or in deposition strata that are too thin. However, the methane contained in such formations represents an extensive gas resource that has good potential for commercial exploitation by advanced drilling and stimulation methods. The MRCP began in late 1977 to provide research, development, and demonstration incentives to encourage methane recovery and use from both minable (in conjunction with improved mine safety and productivity) and unminable coal formations. The complete DOE project also includes the aspect of mine development, which was formerly a USBM program.

The UGR program will build on the previous work of industry and the scientific community to resolve existing technological barriers for effective recovery of natural gas from Devonian shale and methane from coalbeds. Upon completion of these projects, the technology developed jointly with industry is expected to result in wide-scale recovery and use of these new sources of natural gas.

Because of the continuing R&D studies associated with this natural gas program, a complete current listing and discussion of all activities is not possible. The METC operates an open-file system for UGR projects; therefore, further information may be obtained by writing UGR Program, % Ms. R.D. Manilla, U.S. DOE/METC, P.O. Box 880, Morgantown, WV 26505.

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TABLE 4 – PILOT-SYSTEM PROJECTS FOR COALBED METHANE DRAINAGE AND USE

			RECOVERY TECHNIQUE						UTILIZATION			
PILOT SYSTEM[1] PROJECT	PREDRAIN	GOB	Vertical Borehole	Directional Borehole	Horizontal Borehole	Hydraulic Fracturing	Foam Fracturing	Gas Fracturing	Pipeline Injection	Power Generation	Heating Application	LNG Conversion
MINABLE												
Westinghouse		X	X							X		
Westinghouse	X	X	X							X	X	
Occidental/Island Creek	X				X				X		X	X
U. S. Steel	X		X			X	X		X			
Clinchfield	X		X			X			X		X	
J & L Steel	X			X			X		X			
A								X				
UNMINED												
Mountain Fuel	X		X				X		X			
Waynesburg College	X		X				X		X			
Penna. Energy Resources Inc.	X		X				X		X			
Intercomp/Coseka	X		X			X	X		X			

[1]Project A is currently in the planning stage; specific contracts have not yet been negotiated.

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SI Metric Conversion Factors

$$
\begin{array}{rlll}
\text{cu ft} & \times\ 2.831\ 685 & \text{E}-02 & = \text{m}^3 \\
\text{ft} & \times\ 3.048^* & \text{E}-01 & = \text{m} \\
\text{gal} & \times\ 3.785\ 412 & \text{E}+00 & = \text{dm}^3 \\
\text{in.} & \times\ 2.54^* & \text{E}+01 & = \text{mm} \\
\text{sq mile} & \times\ 2.589\ 988 & \text{E}+00 & = \text{km}^2
\end{array}
$$

*Conversion factor is exact.

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